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Case study

Archaeoacoustics of intangible cultural heritage: The sound of the *Maior Ecclesia* of Cluny

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ABSTRACT

Some major historical heritage which has disappeared over time can currently be recovered in part thanks to computer modeling tools and virtual reality technologies. Incorporating sensory experience using immaterial reconstruction constitutes a new form of knowledge and a major methodological change in the field of cultural heritage. Archaeoacoustics are used to introduce phenomenology as a new method for the analysis of historical heritage, allowing evaluation of the sound quality of a space based on subjective perception by using auralization techniques which allow cognitive and physical elements to be reproduced and combined. This study assess and recover the acoustics of a now extinct major religious space: the *Maior Ecclesia* in Cluny, recognised as European heritage. Its long reverberation times produced a grandiose acoustic experience of Gregorian chant, heightening spirituality. Its extensive choir served as a place of spatial reference, because of its location in the temple and its major role in the liturgy. It could be defined as an *ecclesiola in ecclesia* with an identity of its own. The sound of the Gregorian chant of the monks was perceived clearly and powerfully within this space. However, the high reverberance perceived in the rest of the spaces of the church transformed the chant into an unintelligible, inaudible signal.

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1. Research aims

The main aim of this study is the assessment and recovery of the lost intangible heritage of church acoustics through the acoustic reconstruction of religious spaces of the past, which no longer exist. Auralization techniques are used to explore the importance of sensory experience and the spatial dimension of sound, establishing a relationship between the spatial configuration of the church and how this complements the music. To do this the acoustic characteristics of the now non-existent major Romanesque religious space, the *Maior Ecclesia* of Cluny, are assessed. The acoustic reconstruction includes two audio archives based on auralizations.

2. Introduction

The application of new technologies to cultural heritage has led to important methodological changes in the conservation, protection, enhancement and appreciation of monuments. This new approach is stated in the objectives of the International Council on

Monuments and Sites (ICOMOS) [1] which aims to restore meaning and preserve the memory of historic buildings, promoting the application of technology in the assessment of monuments, particularly interesting in the recovery of archaeological heritage.

Experiential archaeology [2] makes “being there” possible. With this aim in mind, numerous studies focused on visual reconstruction [3], illuminating cultural heritage sites [4] or 3D architectural reconstructions [5], using image-based 3D modeling to record archaeological landscapes [6], excavations [7] and monuments [8]. However, all facets of cultural heritage must be researched, incorporating sensory experiences through intangible reconstruction [9], the virtual recreation of heritage settings where intangible values are elements to be protected [10]. The New Technologies for Cultural and Scientific Heritage of the European Commission report [11] states that virtual reality (VR) will provide “an impressive, immersive, interactive and involving product” and will give a “sense of personal presence of the user in its environment”. Thus, the application of VR technologies to cultural heritage [12] has become a powerful tool for archaeological reconstruction.

Within this context, archaeoacoustics [13] arose as a new discipline, capable of enriching the intangible heritage of the past by applying “sensual technology” to a diverse range of monuments, from megalithic structures [14], searching for acoustic

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significance [15], or the effect on the emotional sphere of human consciousness [16] to recovering the sound of the past in spaces of worship. Research in these worship spaces has followed different approaches: the analysis of the relationship between architecture and acoustics in their current condition [17]; the suitability of the acoustics for the Liturgy of the Word [18]; acoustic reconstructions of disappeared religious spaces [19]; the acoustic analysis of the relationship between church spaces and the liturgical function of extinct [20] or currently transformed configurations [21]; assessing subjective characteristics and the study of intentionality behind the acoustics of existing church spaces [22]; the anechoic recordings of ancient music to be used in church auralization [23]; or applying sensory theory to the liturgy [24].

3. Case study: the Maior Ecclesia of Cluny

Cluny Abbey played a crucial role in the Middle Ages, from its foundation in the year 910 until the late 12th century. Seen as the soul of the Middle Ages because of its major religious, political, and cultural importance in the period and its major role in the unity of the Christian West, it was awarded the European Heritage Label by the European Commission. The Benedictine Abbey of Cluny prompted a profound renewal of monastic life, based on the ceremonial splendour of the liturgical celebration of the Mass and the Divine Office. This is why three churches were built in Cluny between the 10th and 12th centuries, each larger than the preceding one. The last of these buildings, the *Maior Ecclesia*, was built in 1130 and destroyed in 1790. Its large dimensions meant that the

celebration of the liturgy took on unprecedented splendour, and it was a major cultural monument, key to the understanding of Romanesque architecture [25], the first European artistic style.

The *Maior Ecclesia* of Cluny imposed the new model of Romanesque basilica, larger than early Christian basilica, predominantly vertical, and paying greater attention to the transept, symbolically opening the space upwards. The floor plan was a Latin cross with two transepts, a central nave over 30 metres high with a barrel vault, flanked by side naves either side, with rib vaults, and an ambulatory from which chapels radiated (Fig. 1) in a solid stone structure with few decorative elements.

The formal scheme responded to monastic needs with a shallow chancel and a main altar for celebration, and a wide choir in the central nave for chanting divine office. In early Christian basilicas the choir in the chancel interacted with the *schola cantorum*, for chanters and minor clergy, situated in the central nave. In the 11th and 12th centuries the choir in the *schola cantorum* merged with the choir in the chancel. Due to the growth of monastic communities they no longer fitted in the chancel and were moved to an enclosed choral structure in the central nave, the choir, which in the case of the *Maior Ecclesia* of Cluny could accommodate approximately 470 monks [26].

The documentary source for the reconstruction of the church is based on the pioneering archaeological work of K.J. Conant [27], the subsequent reconstruction of Cluny [28] and the virtual reconstruction of the environment using a virtual immersion digital model to reconstruct the architecture of Cluny within the Gunzo interdisciplinary project [29,30]. However, a recreation of the sound of the

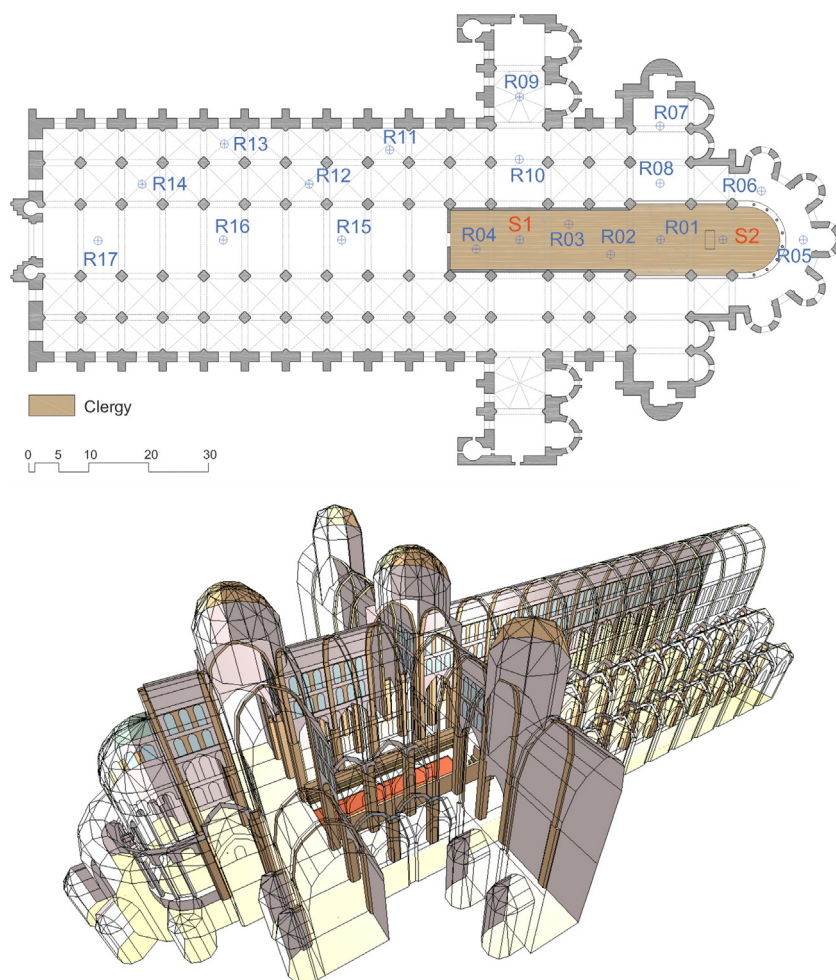


Fig. 1. Top: floorplan of the *Maior Ecclesia* of Cluny. Clergy zone and distribution of sound sources and receivers. Bottom: acoustic 3D model.

Maior Ecclesia of Cluny is still pending in order to complete this recovery of historic memory.

The *Maior Ecclesia* of Cluny was a monumental building in which the ceremonial splendour of the mass was celebrated. This took place in a space that covered the chancel and the choir and was enclosed in the first four stretches of the central nave, where divine office was mainly developed through chanted prayer. The rest of the church was a free space reserved exclusively to monks, with no laymen allowed, where procession, the basis of monastic life, was developed. The Cluny choir constituted the musical avant-garde of the time, with the singing of Gregorian plainchant, a purely melodic and initially monodic style into which more complex developments such as *organum parallelum*, were incorporated, adding other parallel voices in strict melodic and rhythmic concordance, although polyphony was never fully employed.

4. Methods

Acoustic prediction techniques based on computerized models of the space were used (Fig. 1) to reproduce the third Romanesque church of Cluny through its geometry and location of source and receivers, depending on the type of occupation. Equally, interiors were documented using the surviving material from the *Maior Ecclesia*, as well as virtual reconstruction [28] and the pilgrimage churches built to resemble Cluny (e.g. Saint Sernin of Toulouse and Saint Martin of Tours). A subsequent study of characteristics (texture, porosity, finishing) was carried out and absorption and scattering coefficients were assigned to the materials based on main databases and bibliographical references [31–33].

The simulations of the church space provided the room impulse response (RIR) for each receiver, allowing the implementation of high quality auralizations and offering complete information on the acoustic conditions of the church. Once the RIR was obtained the major acoustic parameters of the acoustic field could be deduced and audio signal samples generated for use in subjective assessments or auralizations. This process made it possible to obtain a virtual acoustic reconstruction of these spaces, including the incorporation of acoustic characteristics as another important aspect of its intangible heritage. The simulation software used was CATT-Acoustic, v. 9.0 c, with TUCT (The Universal Cone Tracer) v. 1.0 [34].

4.1. The acoustic model

The acoustic model simulated using CATT-Acoustic has 5220 planes and a volume of close to 110,000 m³ (Fig. 1). The simulations carried out provide the characteristics of the acoustic field in the configuration of the daily celebration of divine office with the monks in the choir. Two omnidirectional source positions were placed at a height of 1.50 m corresponding to the main liturgical spaces of the church, the lectern of the choir, as a representative point where the monks chanted (S1) and the chancel where mass was celebrated at the altar (S2). Seventeen receiver positions were adopted (Fig. 1) and distributed in different spaces throughout the church: the choir (R1 to R4), the ambulatory (R5 and R6), the minor transept (R7 and R8), the major transept (R9 and R10), the side naves (R11 to R14) and the central nave (R15 to R17), all at a height of 1.60 m to represent a person standing. Each surface in the space was assigned a material and its corresponding absorption and scattering coefficient (Table 1), and sound energy absorption through the air contained in this large space was also taken into account.

Following the simulation of the acoustic model generated, the main acoustic objectives defined in ISO 3382-1:2009 [35] were assessed and put into relation with subjective perception characteristics. The physical reverberation of the church space was

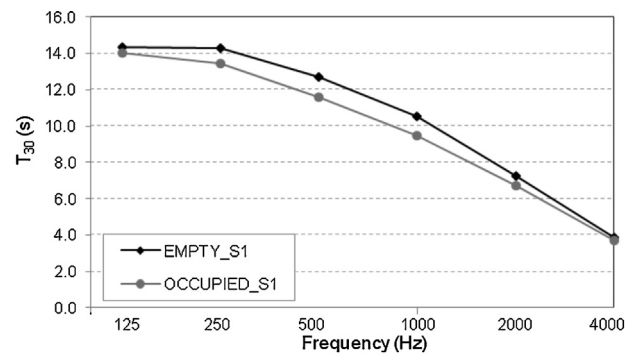


Fig. 2. Octave-band values of average reverberation time T_{30} : empty and occupied. Source in choir (S1).

calculated using reverberation time (T_{30}), while perceived reverberation was correlated to the Early Decay Time (EDT) parameter. The clarity perceived for music was related with Clarity (C_{80}) and Center Time (T_s), which measure the relationship between early and late energy reaching the listener. The perceived acoustic level is assessed through Sound Strength (G), which makes it possible to measure the potential for amplification in the space, as well as evaluating the sound field and the spatial sensation relating to the width of the source through Early Lateral Energy Fraction (J_{LF}). All parameters were spectrally averaged following ISO guidelines.

The discrimination of the sensation perceived by listeners was evaluated using just noticeable difference (JND), defined as the smallest detectable difference between a starting and secondary level of a particular sensory stimulus. JND values established were determined in accordance with the usual conditions of concert halls or theatres, spaces with reverberation times oscillating between 0.5 and 2 seconds. However, in spaces with greater reverberation such as church spaces, the subjective threshold perceived could be different, as stated by Martellotta [36], who has established a different JND value for C_{80} and T_s .

5. Results and discussions

The vast volume of the church of Cluny: 110,000 m³, its complex space and the interior use of highly reflective coating materials favoured long reverberation times, with mid frequency values, $T_{30, mid}$, of 11.6 s (Fig. 2) in the empty church, which decreased to 3.8 s at high frequencies due to the noticeable sound absorption of air.

The increased volume usually involves high levels of reverberation time. The Gothic Basilica of San Petronio in Bologna, with a volume of 170,000 m³, has a measured value of $T_{30, mid}$ of 10.7 s [17]. The same occurs in the case of reflective coatings, as can be checked from the measured values of the Romanesque Cistercian Abbey of Le Thoronet, with a volume of only 11,000 m³, averaged value of T_{30} is 7.7 s [37].

The reverberation time of the space, T_{30} , was practically independent from the sound source position, unlike the Early Decay Time (EDT) of sung Gregorian chant, a parameter that is normally more closely related to the subjective attribute of reverberation. As can be observed in Fig. 3, perceived reverberation with the sound source in the choir was lower in the choir itself, with values around 9.2 s, due to direct sound and the early reflections of the wall enclosing the choir, while it was higher in the central and side naves,

Table 1
Absorption coefficients for materials used.

Material	Surface (%)	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Marble (floor ^a)	14.8	0.01	0.01	0.01	0.02	0.02	0.02
Stone smooth-faced (arches a, pillars b)	27.1	0.04	0.04	0.03	0.04	0.05	0.05
Plaster (walls ^a , vaults ^a)	51.5	0.02	0.02	0.03	0.03	0.04	0.05
Wood (choir ^c [31], doors ^a)	0.1	0.09	0.09	0.08	0.08	0.1	0.07
Windows ^a [32]	3	0.35	0.25	0.18	0.12	0.07	0.04
Audience ^b wooden choir [32]	0.4	0.24	0.40	0.78	0.98	0.96	0.87
Audience ^b area 1.5 pers/m ² [33]	0.4	0.22	0.38	0.71	0.95	0.99	0.99

^a Scattering coefficients 0.12 0.13 0.14 0.15 0.16 0.17.

^b Scattering coefficients 0.20 0.25 0.30 0.35 0.40 0.45.

^c Scattering coefficients 0.30 0.40 0.50 0.60 0.70 0.80.

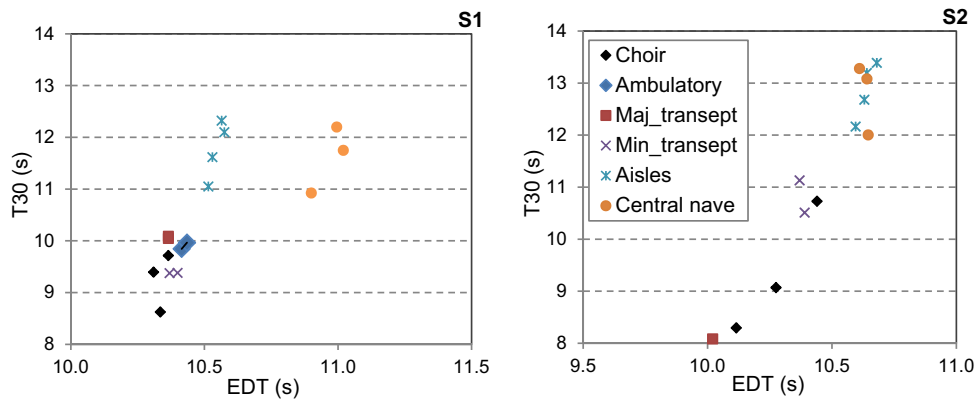


Fig. 3. T_{30} vs. EDT by source and receiver. Values from average 500 Hz–1 kHz.

with differences around 4 JNDs and mean values of 11.8 s. The sound field was noticeably reverberant due to the lack of sound absorption, the huge volume of the church. The chant was unintelligible and incomprehensible, as is shown in Fig. 4, because of a considerable lack of early reflections negatively influencing early-to-late ratios.

These unequal perceptions led to a clear spatial differentiation that was complemented by the analysis of average energy parameters for each zone: Clarity C_{80} , Center Time T_s , along with sound Strength G and apparent source width J_{LF} (Table 2). This was completed with the standard deviation value that allowed assessment of the spatial scattering of each parameter.

5.1. Sound source in the choir (S1)

With the sound source placed in the choir (S1), average C_{80} values in the choir area were 0.43 dB; average sound strength was 4.86 dB; spatiality was fair with mean J_{LF} values of 0.20; and high Center time T_s was 356 ms. The enclosed choir favoured early reflections and increased sound strength and spatiality, although

the clarity reached its highest values in this area, the excessive reverberation caused poor results for this parameter. Singing the Latin text in a slow rhythm with added emphasis on stress and punctuation improved intelligibility by adjusting the sound to the high reverberation time.

The large number of monks in the choir increased the number of sound sources during the liturgy which, combined with the amplifying effects of the enclosed choir space, allowed the voices of the monks to be projected with a high acoustic level in the church. In the other parts of the church the singing generated a weakened sound with practically zero intelligibility, as can be deduced from the mean values for C_{80} , which oscillated between -9.4 and -20.0 dB, a difference of between 7 and 14 JNDs with respect to the values obtained in the choir (Table 3); from lower perceived acoustic levels, with differences of mean values for G of up to 3 JNDs in the naves; and from an apparent lack of directionality and clarity, with mean values of T_s between 730 and 950 ms.

5.2. Sound source at the main altar (S2)

With the sound source at the main altar (S2), the mean values for C_{80} in the choir area were -6.1 dB, 5.5 JNDs poorer with respect to position S1 (Table 3), and a fair mean sound strength of 5.3 dB was obtained. In the case of masses held on the main altar the content of the spoken word was not as important as vocal changes in terms of pitch and intonation; the liturgy was designed with the monks in the choir in mind, so the musical part of the liturgical action in the choir became richer.

In the other parts of the church, the mean values for C_{80} oscillated between -7.8 and -25.81 dB, causing deficient acoustic conditions for music with an increase of up to 18 JNDs in the side naves.

5.3. Spatial distribution

This assessment of the energy parameters was complemented with Fig. S1 (on line) which shows the mappings for a 1 kHz octave

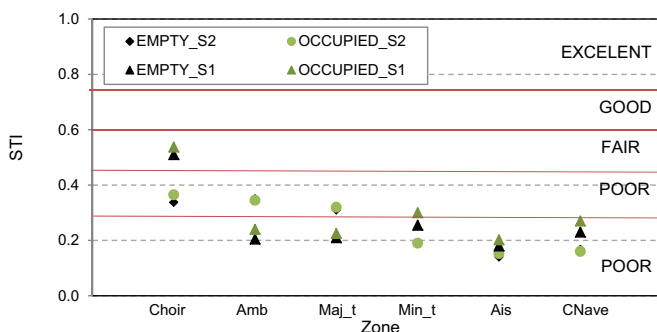


Fig. 4. Speech transmission index (STI) values in different spaces throughout the church for both sound source positions: S1 (choir) and S2 (main altar).

Table 2

Summary of average values and standard deviation of acoustic parameters analyzed. Spatial average values by zone.

Zones	Source	EDT _m (s) ± σ	C _{80m} (dB) ± σ	T _{sm} (ms) ± σ	G _m (dB) ± σ	J _{Lf} ± σ
Choir	S1	10.00 ± 0.33	1.95 ± 1.77	361.04 ± 83.50	4.39 ± 0.69	0.17 ± 0.04
	S2	9.71 ± 0.69	-6.07 ± 1.24	648.23 ± 77.74	4.38 ± 1.10	0.08 ± 0.03
Ambulatory	S1	10.32 ± 0.12	-13.10 ± 2.28	804.04 ± 26.96	2.16 ± 1.66	0.37 ± 0.11
	S2	7.42 ± 0.09	-8.34 ± 0.31	523.56 ± 18.02	8.92 ± 0.12	0.22 ± 0.02
Major transept	S1	10.52 ± 0.08	-16.50 ± 1.99	847.49 ± 16.30	2.11 ± 0.07	0.42 ± 0.00
	S2	8.47 ± 0.03	-7.35 ± 1.35	592.82 ± 18.18	7.79 ± 0.21	0.05 ± 0.01
Minor transept	S1	9.93 ± 0.18	-22.98 ± 2.21	770.56 ± 16.77	2.84 ± 0.26	0.23 ± 0.06
	S2	11.26 ± 0.29	-14.84 ± 4.45	934.30 ± 86.60	3.79 ± 0.58	0.51 ± 0.12
Aisles	S1	12.29 ± 0.34	-19.94 ± 2.79	1017.72 ± 50.30	0.56 ± 0.62	0.23 ± 0.06
	S2	13.50 ± 0.32	-28.71 ± 1.93	1208.15 ± 47.85	1.14 ± 0.41	0.22 ± 0.11
Central nave	S1	12.22 ± 0.36	-9.10 ± 1.41	877.73 ± 75.06	1.35 ± 0.81	0.05 ± 0.09
	S2	13.42 ± 0.30	-13.16 ± 0.47	1119.06 ± 37.10	1.61 ± 0.43	0.09 ± 0.06

band frequency on the audience plane, making it possible to verify the variation of each acoustic parameter and the spatial distribution patterns, reflecting the two spaces defined: the space for the clergy, made up of the choir and chancel, and the rest of the church as a processional space.

A uniform distribution of SPL could be observed, due to the reverberant conditions, which gradually decreased as the sound source zone was approached, remaining constant after reaching a specific point. The area for the clergy in the main altar and choir presented suitable acoustic conditions, with sufficient musical clarity C₈₀, allowing the different sounds to be perceived separately, and with considerable sound spatiality. Despite this spatial differentiation the acoustic behaviour of the choir area cannot be understood without taking into account the rest of spaces. The choir should be considered as a coupled volume (small volume connected through small openings to a large main volume with different levels of sound absorption), which behaves acoustically differently from the remaining space. If the sound source is located in the principal space, the sound energy is trapped in the coupled volume, involving late arrival in the principal space favouring an increase in reverberation time and energy parameters. This phenomenon could be considered favourable to Gregorian chant, as sounds lost directionality, generating the feeling of being inside a huge container. The “sacred” character of the churches encouraged listeners to accept, and even prefer longer reverberation times than in concert halls [38].

6. Auralizations

The subjective perception of sound in a space could be obtained through auralization depending on the position of the sound source and receiver and based on a sound signal. The acoustic study is complemented with two audio files reproducing the acoustic conditions in the space of the *Maior Ecclesia* of Cluny considering the sound source in the choir (S1) and the receivers at two different points of the church space, one in the choir: position R3 (*Cluny_S1_R3_choir.wav* on line) and another on the side nave: position R14 (*Cluny_S1_R14_aisle.wav* on line).

The files are the result of the combination of an anechoic recording with binaural simulated responses, processed with Multivolver software, a complementary tool for CATT Acoustic. The anechoic signal is a fragment of 62 seconds of Gregorian chant from the hymn “*Pangue Lingua*” attributed to St Thomas Aquinas, sung in Phrygian mode or *deuterus authenticus*, characterised by a voice modulation, which presents a rich spectrum of mid frequencies and a considerable amount of low frequencies.

The reproduction of this complementary material makes it possible to appreciate the different acoustic and sensory conditions of the two spaces in the church of Cluny. The choir, a space for prayer through Latin chant made it possible to obtain a close sound, a clear timbre, and fair clarity where the syllables and notes of chant are easily distinguished. High reverberation in the church was the main

Table 3

JNDs values by zone.

Zones	Source	T ₃₀	EDT	C ₈₀	T _s	G	J _{Lf}
Choir	S1	0.00	0.00	0.00	0.00	0.00	0.00
	S2	-0.11	-0.59	5.35	-5.91	0.00	-0.82
Ambulatory	S1	-0.03	0.62	10.04	-7.35	-2.23	2.07
	S2	-0.86	-6.97	6.86	-4.14	4.53	0.57
Major transept	S1	-0.07	0.99	12.30	-7.65	-2.28	2.53
	S2	-0.66	-3.63	6.20	-5.21	3.41	-1.19
Minor transept	S1	0.14	-0.14	16.63	-7.09	-1.54	0.59
	S2	0.08	2.23	11.20	-8.18	-0.60	3.42
Aisles	S1	0.39	5.18	20.44	-9.35	-3.24	0.55
	S2	0.39	5.18	20.44	-9.35	-3.24	0.55
Central nave	S1	0.96	3.63	7.37	-7.85	-3.04	-1.13
	S2	0.90	5.09	10.08	-9.03	-2.78	-0.79

Note: JND values were obtained assuming the parameters calculated with the source in the choir as a reference.

reason for the continued distant reverberant sound in the choir, at a lower acoustic level, flowing slowly with no defined limits, seemingly coming from all directions. The juxtaposition of both acoustic aspects increased the apparent spatiality in the choir endowing it with the sacred and majestic nuances of spiritual emotion.

In the rest of the church a distantly reverberating acoustic mass was perceived, which along with the slow energy decay, longer duration, and the accentuation of the Latin syllables generated a temporary superimposition of one voice over the next, bringing about an irregular and confused sound and unintelligible text.

7. Conclusions

Archaeoacoustics allows the sound of a space to be analysed using energy and time acoustic parameters, recovering the acoustic memory and the immaterial atmosphere of the space, and its acoustic dimension within the space as a new approximation to knowledge of intangible cultural heritage. The Romanesque *Maior Ecclesia* of Cluny was a major functional structure, a means of communication with God through sensory perception, with a spacious and resounding framework where the almost unending Gregorian chant could be developed, reflecting the close relationship between liturgy, music and architecture.

The high reverberation, with mid frequency values, T_{30, mid}, of 11 s, favoured acoustic conditions for the development of Gregorian melodic chant. The importance of speech intelligibility is lost and transformed into a mystical aural experience. This grandiose sensory sound experience was deeply spiritual, getting closer to the divine presence through multisensory experience, a very different expression to that of the current demands based on the predominance of visual elements.

The spacious Cluny choir was a place of spatial reference with its own identity, immersed in the space of the church, an *ecclesiola in ecclesia*, a smaller space reserved for the clergy. When the monks

sang Gregorian chant in this space the sound was clear with mean values C_{80} of 0.18 dB, and a mean sound strength of 4.25 dB. Acoustic conditions in the rest of the church were unsuitable, with an unintelligible and incomprehensible reverberant sound. However, these areas had not been designed as areas for audition, but rather as spaces for resonance, diffusion, and amplification of sound, for exchanging energy with the area for the clergy in the choir and the main altar, reverberation spaces that complemented and defined the strictly clerical space.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.culher.2015.12.003>.

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